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EXPERIMENTAL STUDY OF THE CHARACTERISTICS OF PLANAR THIN-FILM S--ETC(U)

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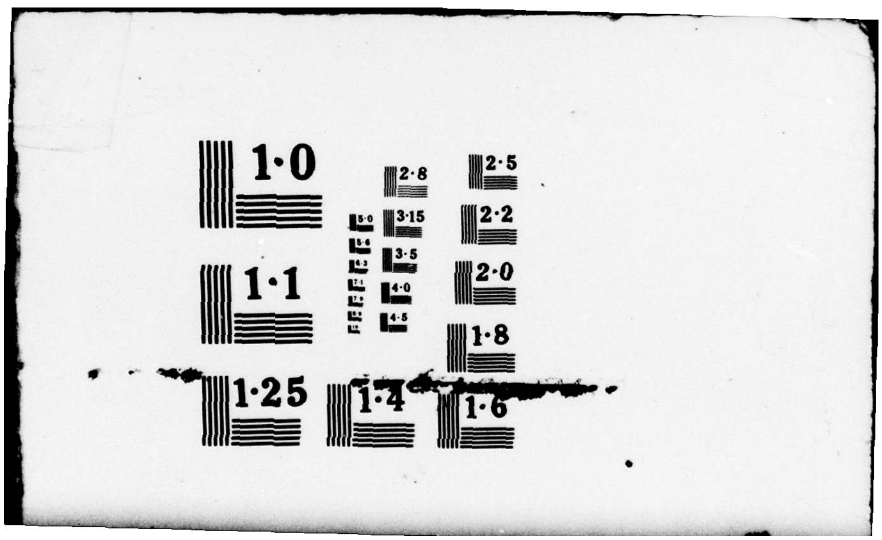
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EXPERIMENTAL STUDY OF THE CHARACTERISTICS OF PLANAR THIN-FILM SQUIDs.

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ABSTRACT

Superconducting Quantum Interference Devices (SQUIDs) have been fabricated as part of a superconducting instrumentation program. Measurements of the characteristics of planar thin-film SQUIDs were made. Inductive coupling and direct coupling between the SQUID and the external electronics were demonstrated. In each case the response to an applied field and the signal-to-noise ratio was determined. Results from the two coupling methods are compared with that possible with commercially available SQUIDs.

I. INTRODUCTION.

Superconducting devices have become increasingly important in research and considerable effort is being directed to their further development. A long-range goal is the development of advanced superconducting instrumentation compatible with flight experiments. Superconducting arrays of Josephson junctions will be studied for magnetometry and radiation detector space applications.

One of the simplest and most useful superconducting devices is the SQUID. SQUID is an acronym for Superconducting Quantum Interference Device. It can be used as an ultra-sensitive magnetometer, low temperature thermometer, voltmeter, galvanometer, and VLF antenna to mention only a few applications.

There are two common SQUID configurations: the point contact type[1] and the thin-film kind.[2] In this report all measurements were made using planar thin-film SQUIDs. Techniques for making reliable thin-film SQUIDs have been developed at NASA/Marshall Space Flight Center.[3] A remaining problem has been how to efficiently couple to the SQUID in order to realize its maximum sensitivity. This report concerns itself with this problem.

II. OBJECTIVES.

The SQUID operates immersed in a bath of liquid helium in order to be in the superconducting state. It is coupled to the external readout electrons by a tuned LC-circuit. The objectives of this work were to optimize the coupling between the SQUID and the tank circuit. Two methods were investigated: direct coupling and conventional inductive coupling (mutual inductance between the SQUID and the tank circuit). A determination of

the SQUID sensitivity and the noise present was made for both coupling methods to give an indication of the coupling efficiency. Direct coupling has not been thoroughly studied and is of interest because a direct coupled thin-film SQUID can be used in the readout system for the superconducting gyro-relativity experiment.

III. EXPERIMENTAL.

Devices.

The SQUIDs tested were made of niobium sputtered onto glass microscope slides. This process is described elsewhere.[3] Topologically the device is a circular loop (ID ~ 0.6 mm and OD ~ 0.8 mm) interrupted by a weak-link microbridge. A typical SQUID is shown in Figure 1. Some SQUIDs were overcoated with germanium to keep them from accidentally being shorted. In certain instances this also extended this operating temperature range. This work has been described previously.[4] All SQUIDs were handled with abandon. None was damaged by any experimental procedures used and no aging effects have been observed.

Apparatus.

To facilitate rapid testing of SQUIDs a co-axial stainless steel test probe was made. It is shown in Figure 2. The probe contained the rf-tank circuit and a small micarta block to which the SQUIDs were affixed. The lower end of the probe extended into the liquid helium dewar. Its position could be varied to temporarily adjust the temperature of the SQUID to a valve above 4.2.K. The SQUID and the tank circuit were enclosed by a cylindrical niobium shield to reduce magnetic and electrical interference.

Operation of SQUID.

The SQUID is basically a superconducting loop. F. London[5] showed that

the flux threading through a superconducting loop is quantized in units of the flux quantum ϕ_o, where

$$\phi_o = \frac{h}{2e} \sim 2.07 \times 10^{-15}$$

webers. Here h is Planck's constant and (2e) is the electron-pair charge. This means that the flux must be an integral multiple of the basic flux quantum ϕ_o; that is, $\phi = n\ \phi_o$ where n is any integer. If the superconducting loop is weakened by an extremely narrow constriction at one point, then it is possible, by applying an external field, to force non-integral multiples of flux through the loop; e.g., $(n + 1/2)\ \phi_o$.

The difference in energy between integral and non-integral multiples of ϕ_o is called the Josephson coupling energy. The narrow constriction (microbridge) is called a Josephson junction. Brian Josephson predicted this coupling energy in 1962.[6] The flux through the SQUID can be controlled by the tank circuit coil. States of minimum energy are $\phi = n\ \phi_o$; those of maximum energy are $\phi = (n + 1/2)\ \phi_o$. If the flux $\phi = n\ \phi_o$ is varied above or below this value, the SQUID will generate an opposing field to this variation. Conversely if the applied field is varied about a maximum energy value $(n + 1/2)\ \phi_o$, the SQUID generates a field which adds to this variation. These energy contributions by the SQUID, either opposing or aiding the applied field, mean that in the first case the SQUID behaves diamagnetically, while in the latter case it behaves paramagnetically. In both cases it modulates the inductance of the tank coil. This impedance variation is periodic in the externally applied field, with the period being the flux quantum ϕ. The voltage across the tank circuit is a function of the flux through the SQUID and can be detected with suitable electronics. This explanation is due to Zimmerman.[7]

Electronics.

The electronics used was a commercial unit manufactured by the S.H.E. Corporation.[14] This unit attached directly to the SQUID probe. A block diagram of the electronics is shown in Figure 3. An rf-current source is weakly coupled to the tank circuit at its resonant frequency of 19 MHz. The voltage developed across the tank circuit is amplified, detected, and displayed in one of two modes. If the detected voltage is displayed as a function of the rf-drive current then we have "steps" shown in Figure 4. If the rf-voltage is fixed and the detected voltage is displayed as a function of the magnetic flux in the SQUID, then we observe a triangular pattern shown in Figure 5.

To check sensitivity and noise the SQUID was operated in a flux-locked loop. The detector output was fed to a lock-in amplifier synchronized with the audio oscillator which modulates the flux in the SQUID. The lock-in output is fed back to the rf-coil and maintains the flux in the SQUID at an extremum of the triangular pattern. This permits evaluation of the SQUID sensitivity, system calibration, and insures that the SQUID is operating in a linear range.

Coupling Characteristics.

The criteria used here are those posted by Sullivan.[9] Coupling efficiency was checked by noting the spacing between the triangular patterns shifted vertically on an oscilloscope. A typical trace is shown in Figure 5. One criterion for good coupling is that β (defined as $2\pi Li_c/\phi_o$) should lie between 1 and 10. An approximate determination of β is to find the ratio of peak-to-peak signal height to the height of this signal above the zero reference level, or A/B where A and B are defined in Figure 5.

Another condition for optimum coupling is that the product $k^2Q \approx 1$,

where $k = M(L_t L_s)^{-1/2}$ and is the coupling between the tank coil L_t and the SQUID L_s, and Q is the quality factor for the unloaded tank circuit.[9,10] The value of k^2Q is experimentally determined by noting the appearance of the triangles as well as their spacing in Figure 6. Well defined triangles with sharp extremes and small (with respect to peak-to-peak signal height) vertical spacing occur for $k^2Q \approx 1$. For $k^2Q < 1$ the triangles are clipped and the vertical spacing between patterns is increased. For $k^2Q > 1$ the triangles are rounded and again have large vertical spacing.

The best sensitivity obtained is shown in Figure 7. Here the SQUID is operated in the lock-on mode. Calibration is effected by momentarily unlocking the system and allowing the triangular pattern to move across the screen of the monitoring oscilloscope. When one triangle has moved across the system is relocked and the change is vertical displacement noted. Alternatively a small (known) current was fed into the rf-coil and adjusted to cause a shift of one triangle on the oscilloscope. This current was approximately 900-1000 nanoamperes per flux quantum. Both methods gave the same results within experimental limits. Using the latter method smaller and smaller currents were applied until the resulting signal could no longer be distinguished from the noise. Our best results allowed detection of $10^{-3}\ \phi_0$. This is shown in Figure 7.

Inductive Coupling.

Conventional inductive coupling between the SQUID and the rf-tank coil was studied initially. Previous work[8] indicated that the planar SQUIDs coupled well using a pancake coil of copper wire. The coil was affixed to the glass slide directly over the thin-film SQUID with masking tape. It was emperically determined that about 13 turns of the 0.005" diameter copper

inductance is quite small and the stray inductances become important. Preliminary calculations indicate that direct coupling and inductive coupling are entirely equivalent and thus, with some effort and ingenuity direct coupled SQUIDs may rival inductively coupled SQUIDs.

Successful operation of direct coupled SQUIDs has not been a problem. All the SQUIDs tested by direct coupling have worked. None has had a good (10:1) signal-to-noise ratio and thus far we have not been able to lock-on to one to determine its sensitivity. Some representative data are shown in Fugure 9. Our best results occurred for a tank coil of 5 turns $L \approx 0.2$ μH and a tank capacitance of 372 pf. It was thought that lower inductance coils or coils made using super conducting wire might improve this performance, but this has not been tried. As can be seen from Figure 8, the signal-to-noise ratio is poor, and must be improved if this method is to be useful. Unfortunately all SQUIDs tested so far have not worked immersed in the helium. This means that the height of the probe above the liquid helium must be adjusted frequently in order to maintain the SQUID near its operating temperature. This causes some problems in proper tuning of the electronics and in having time to check the sensitivity before the temperature shifts and the SQUID must be returned. A plot of the signal response as the temperature increases is shown in Figure 9. Also shown are some additional traces made by replacing the 1 hKz sweep frequency with sweep of 0.2 Hz in order that the SQUID output could be recorded on the X-Y recorder.

CONCLUSIONS AND RECOMMENDATIONS.

Preliminary studies have shown that using inductive coupling it is possible to couple well to the planar thin-film SQUIDs using pancake coils. The best sensitivity is $10^{-3}\ \phi_0$. Approximate rms noise is $10^{-4}\ \phi_0$ per root hertz.

wire gave the best coupling. Pancake coils with varying numbers of turns (4-17) were tested, but increasing or decreasing the number of turns from 13 did not significantly improve the coupling. At either extreme a signal could be observed, but the signal-to-noise ratio was degraded.

Considerable effort was made to improve this coupling. The only significant improvement was to use a sinular coil, but replace the 0.005" diameter copper with 0.005" diameter niobium wire. At best this brought about an improvement in sensitivity of approximately 50%. At worst the sensitivity was the same. The one drawback was that the circuit Q was high and this made tuning difficult.

Special coil forms were made using bylon as a former. These allowed us to wind very uniform close-wound coils of niobium and copper which could be accurately positioned with respect to the SQUID. Unfortunately this did not lead to coupling improvements.

Direct Coupling.

Although much work has been done on inductively coupled rf-SQUIDs, very little can be learned from the literature concerning direct coupled rf-SQUIDs. Brief mention was made in one paper.[11] The inductively coupled SQUID modulates the tank coil inductance. The Q($\approx$ 100) of the circuit helps to offset the weak coupling ($k \approx 0.1$) between the SQUID and the tank coil. In general inductive coupling allows the use of many (>10) turns for the tank inductance. For direct coupling the tank coil must have a small inductance as compared to the SQUID inductance in order that the changes in the SQUID inductance will have a large effect on the tank circuit. Experimentally this is difficult because as the inductance is reduced, the capacitance of the tank circuit must be increased in order to maintain the proper resonant frequency. Also the SQUID

This is comparable to the best commercially available thin-film SQUIDs.

Progress with direct coupling to the SQUIDs has suffered due partly to a lack of time. Direct coupling is possible and with only modest effort signal-to-noise ratios comparable to those obtained with inductively coupled devices is possible.

Future work must be done on direct coupled SQUIDs in order to improve the signal-to-ratio. The use of one or two turn inductors and large capacitors in the rf-tank circuit may solve this problem. Also the use of SQUIDs with lower operating temperatures will help. To this end more thin-film SQUIDs will be made.

Inductively coupled SQUIDs appear to be well coupled and are as sensitive as commercially available thin-film devices. Future work will involve the use of a "flux-funnel" to permit tighter coupling to the SQUID.[12]

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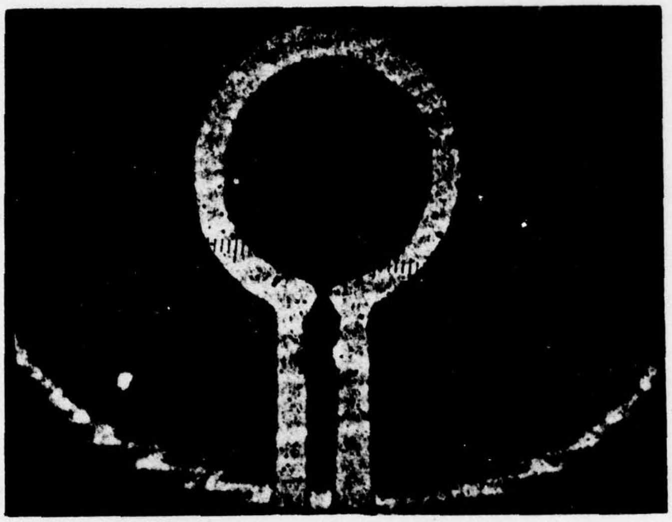


FIGURE 1

A 50x enlargement of a typical planar thin-film SQUID. Each scale division is approximately 0.02 mm. Note legs extending from SQUID to facilitate soldering and the scratch through the weak link. Experimental determination of the inductance gave a value of 3×10^{-10} H which agrees within experimental errors to a theoretical value of 6×10^{-10} H. See reference 13 for details.

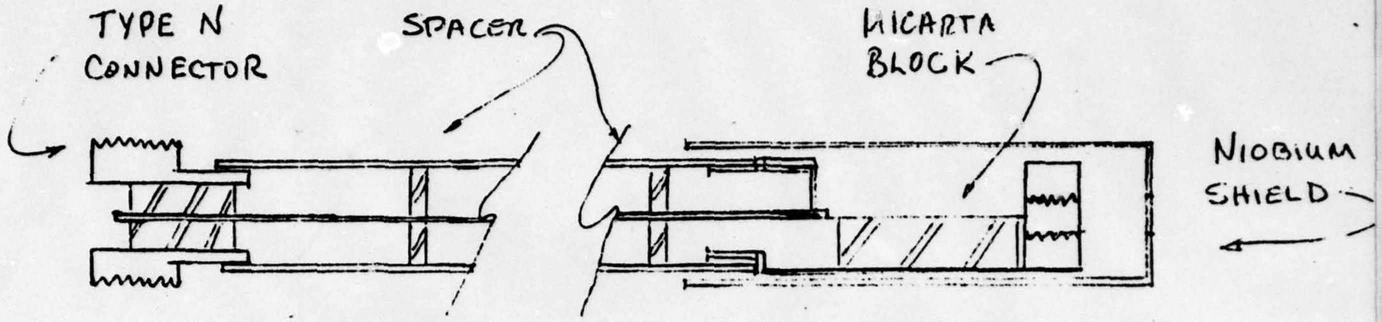


FIGURE 2

Sketch of SQUID probe. (Not to scale).

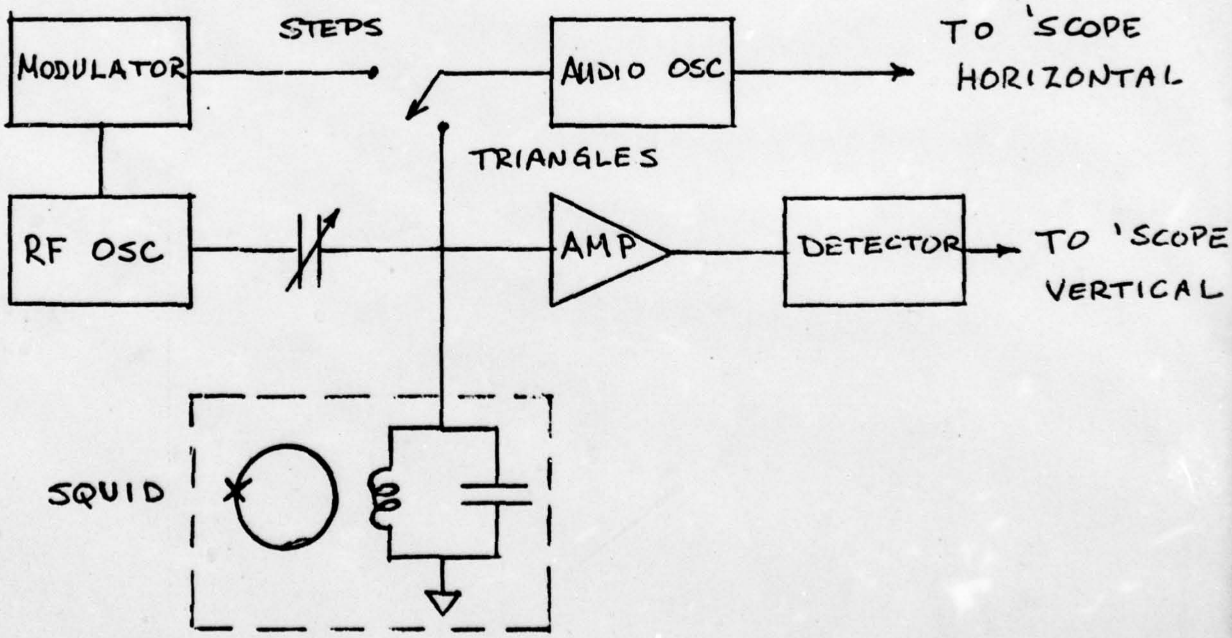


FIGURE 3

Block diagram of components used in rf-biasing the SQUID. Section within dashed lines is at 4.2K. The tuned circuit is weakly coupled by means of a small variable capacitor to a 19 MHz oscillator. The voltage across the tuned circuit is amplified and detected.

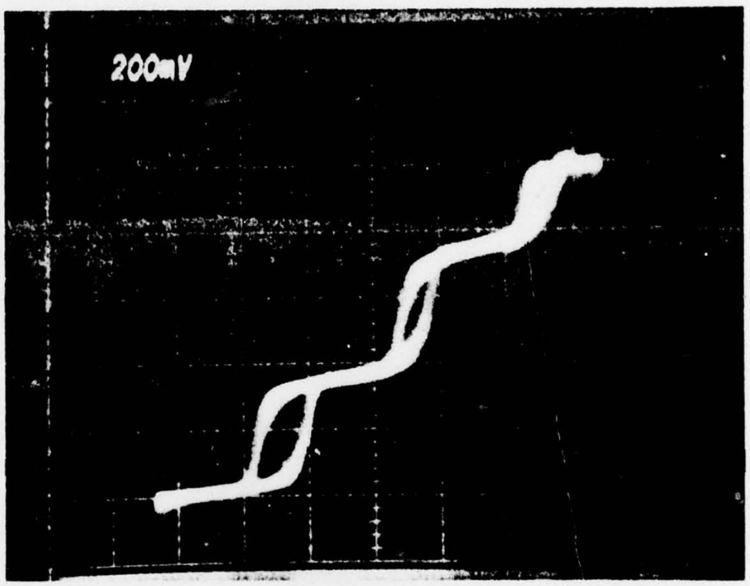


FIGURE 4

Step pattern for a well coupled SQUID. The two traces represent the extreme values of the patterns observed as the average flux in the SQUID is changed. The vertical axis is proportional to the detector voltage, the horizontal to the rf-drive voltage.

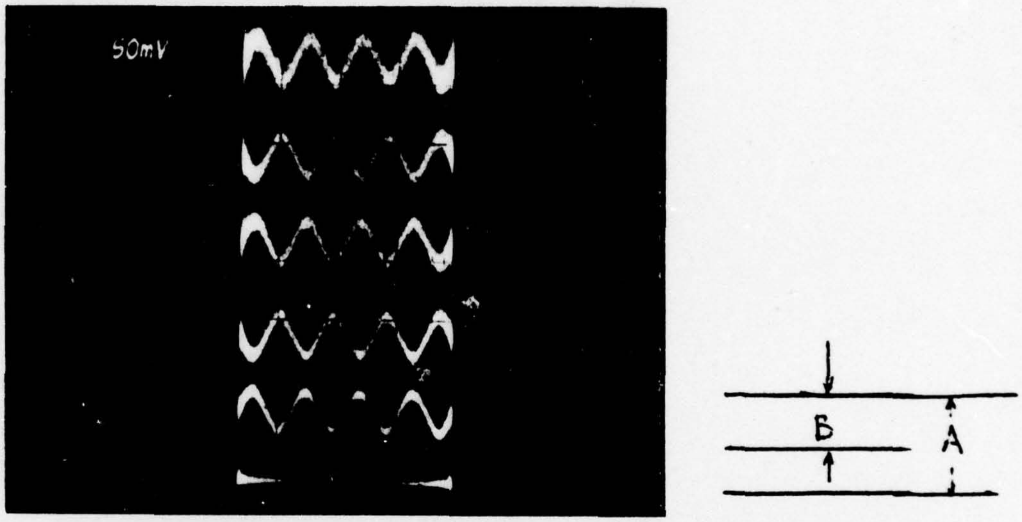


FIGURE 5

Triangle pattern for different rf-biasing. The horizonal axis is proportional to the average flux in the SQUID, the vertical to the rf-voltage level. The rf-voltage is varied by adjoining the coupling capacitor between the rf-oscillator and the tuned circuit.

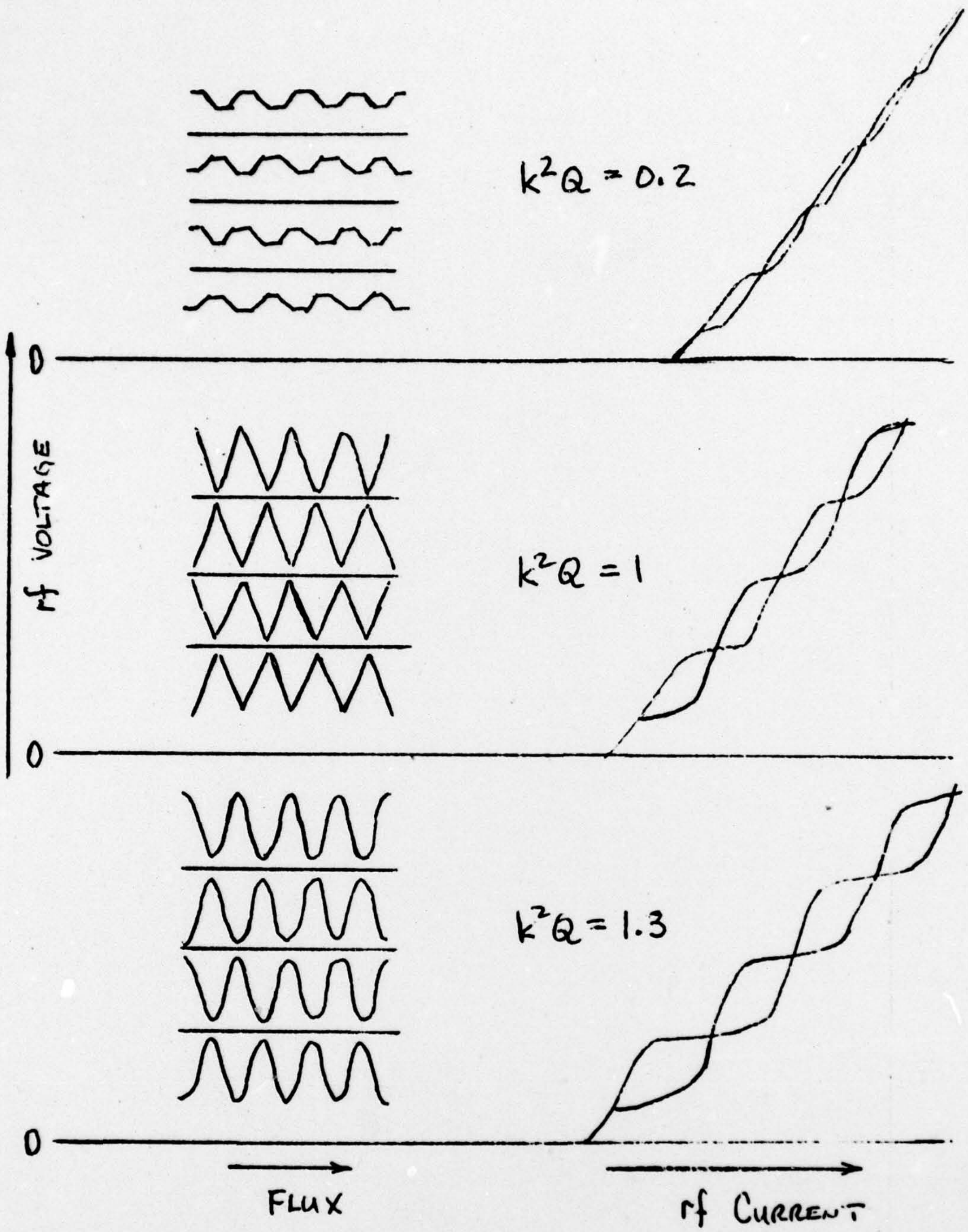


FIGURE 6

Variation of SQUID response with k^2Q. Optimum coupling is achieved for $k^2Q \approx 1$. The form of the display allows one to discern whether the coupling is too strong or too weak. (From reference 9)

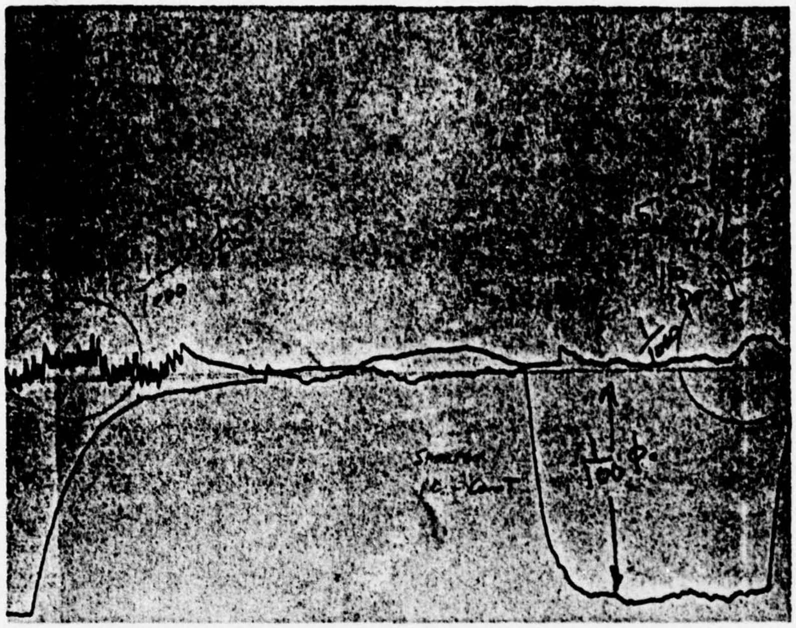
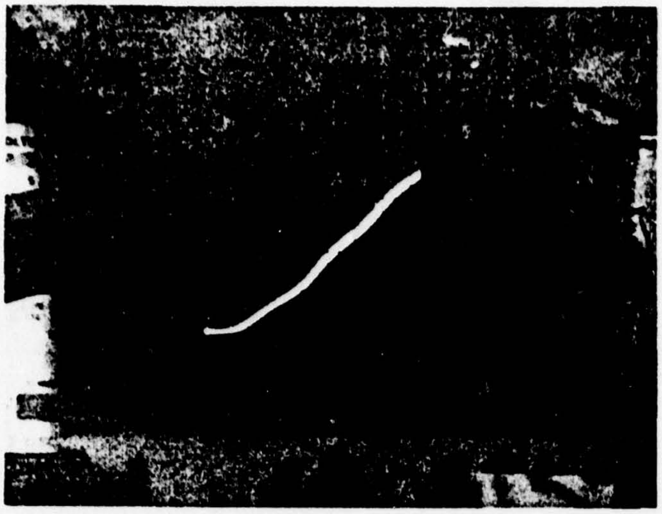
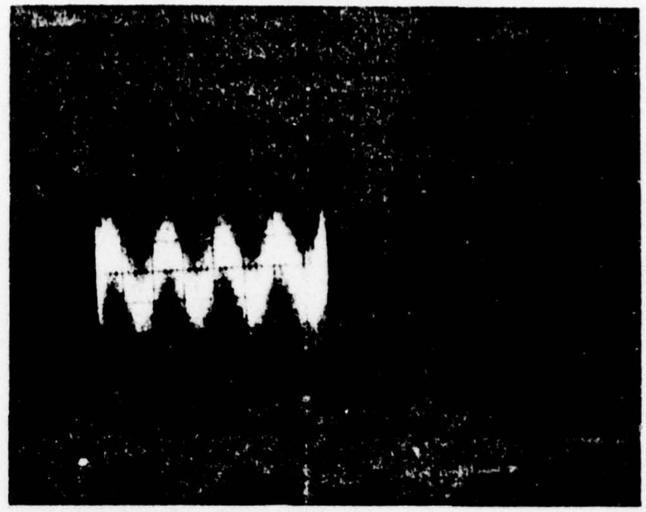


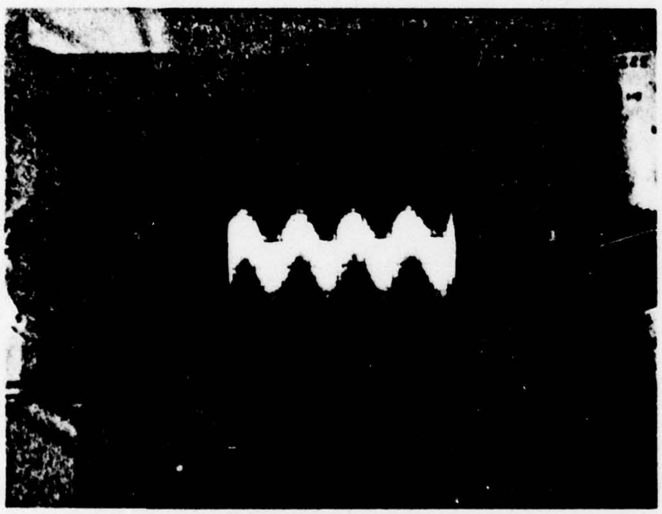
FIGURE 7

SQUID response vs time. The SQUID is operated in the lock-on mode. The vertical axis is the lock-in output.

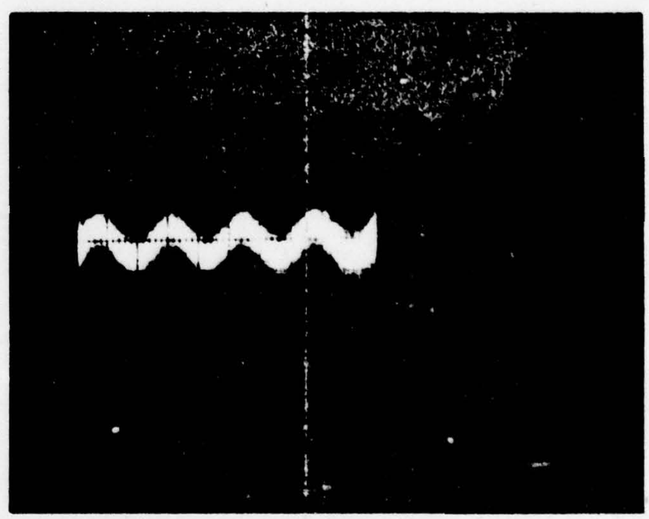




10 mv/cm



20 mv/cm



10 mv/cm

FIGURE 8

Characteristic Steps and Triangles from Cirect Coupled SQUIDs. The horizontal sweep rate is 1 kHz. Poor signal-to-noise is evident in the triangular patterns. The vertical gain is given below each triangular pattern.

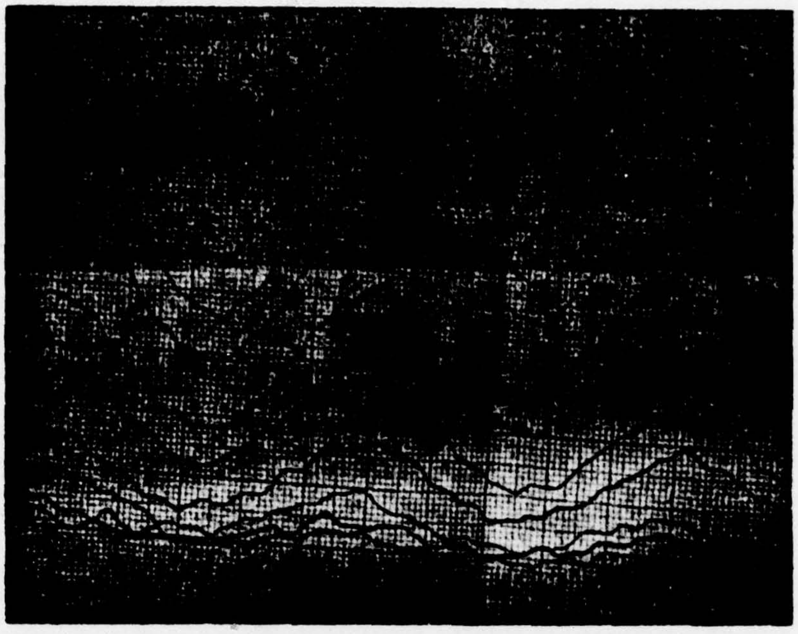
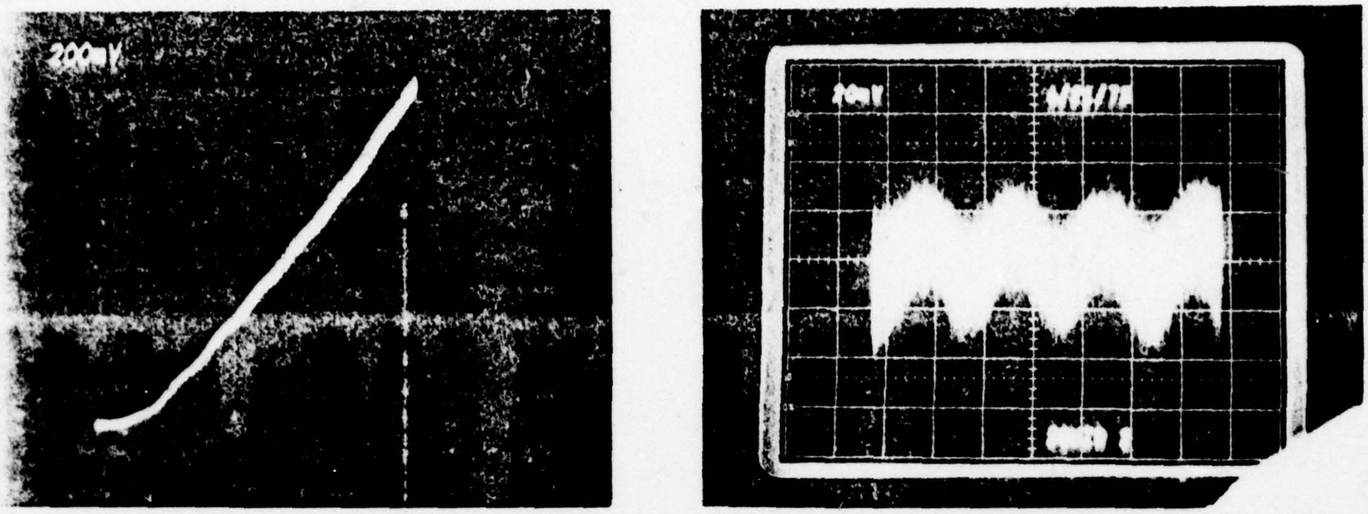
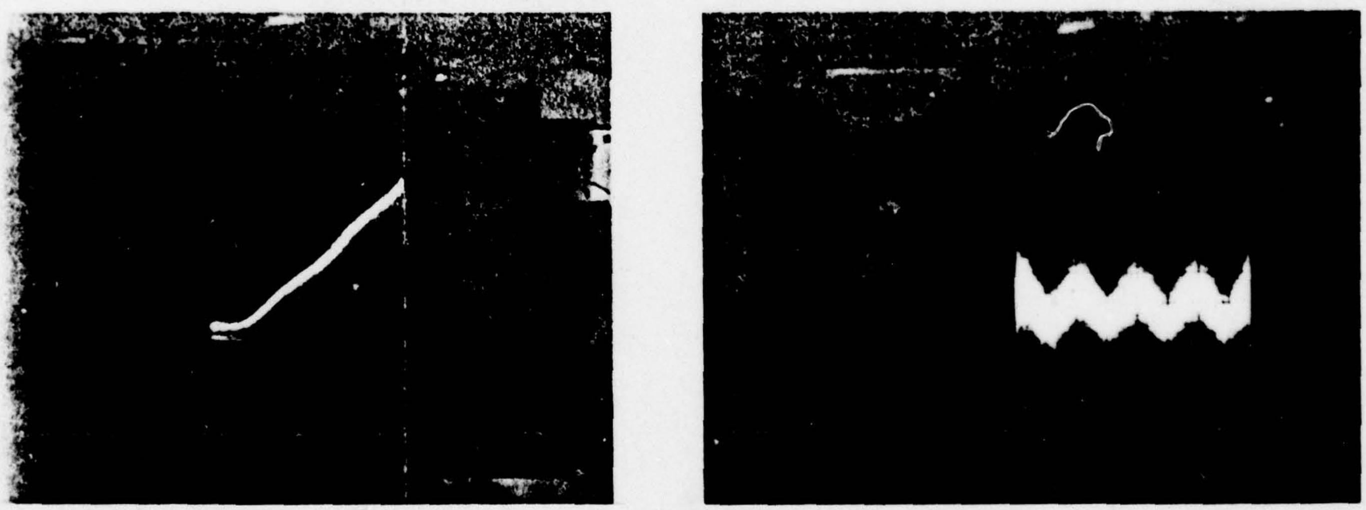


FIGURE 9

Triangular Pattern made using a slow sweep (0.1 Hz) in order to use the X-Y recorder. Vertical axis is proportional to the detected voltage, the horizontal to the average flux in the SQUID. As the temperature changes the SQUID, response decreases due to the variation of the critical current with temperature.



Inductively Coupled



Direct Coupled

20 mv/cm

FIGURE 10

Some representative pictures of direct and inductively coupled SQUIDs.